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1. It is of utmost importance in the study of the evolution of planets to obtain an absolute time scale for all planets. However, such a scale is available only in regard to the Earth, at a time when the most interesting results could be derived from the study of the cause of geological development of various planets. An attempt is made in this paper to determine the absolute age of certain formations on the surface of the Moon.

For this purpose, it is essential to select any given regular process in time which takes place on the surface of the planet and the results of which would have been subjected to quantitative study. We will concern ourselves here with the bombardment of the surface of the Moon by sufficiently heavy meteorites.

2. A morphological analysis of the lunar surface indicates that a majority of the lunar craters are undoubtedly of a volcanic origin. There exists a specific class of objects, called small craters, which are clearly formations which resulted from falling meteorites. As was indicated by A. V. Khabakov (Ref. 1), the location of the small craters has no relation to the tectonic structure of the surface. These small

craters can be found throughout the entire surface of the Moon, including the bottoms of the so-called seas, the mountainous regions, and in the bottoms of large craters. Our examination of the distribution of the small craters along the bottoms of the seas has shown that this distribution conforms to the Poisson law. The small craters are of a cup-shaped form, and one of their characteristics is the almost complete absence of a bank. The diameter of one of these small craters does not exceed 6 to 7 km. The smallest of these craters (on the borderline of visibility) have diameters on the order of 1 km.

3. If a given sector is bombarded by meteorites of various kinetic energies, then the small craters, which are formed by them, will have a determined distribution along a diameter D, which can be calculated. Let us assume that n(D), which pertains to a time unit, is a theoretical distribution. If N(D) is the observed distribution, then the relation N(D)/n(D) should be constant and should equal the age of the given sector. We will notice that, if the observed distribution is the same as the theoretical distribution, this in turn will then be a proof of the meteoric nature of the small craters, since the volcanic craters have an essentially different distribution with a mode between 20 and 30 km in diameter.

4. According to the theory which was developed by K. P. Stanyukovitch (Ref. 2), the impact of meteorites on the surface of a planet can be considered as an explosion when the planet falls with a speed which exceeds 4 km per sec. The radius of the funnel which is created thereby is related to the mass and velocity of the meteorite by the correlation

$$R^3 = \frac{2A}{3\eta}\frac{k_2 - 1}{k_2 + 1} M \frac{\bar{\delta}}{\delta_{explosives}} \left(\frac{\nu}{\nu_{1m}}\right)^2 \tag{1}$$

Here

R is the radius of the funnel

M is the mass of the meteorite

ν is the speed of fall of the meteorite

k_2, η are the parameters which depend on ν as follows: when $\nu = 5$ km/sec, 10 km/sec, 50 km/sec, $k_2 = 5, 4, 3$, respectively; $\eta = 1/7$ when $\nu = 5$ km/sec and 1/6 when $\nu = 50$ km/sec; $A = 10^3$ in the case of soft ground and $0.2 \times 10^3 - 0.8 \times 10^3$ in the case of rock formations (it was assumed that $A = 0.8 \times 10^3$);

δ is the density of the matter which received the impact (we assume that $\delta = 3$)

$\delta_{explosives}$ is the density of an equivalent explosive matter which equals 1.6

ν_{1m} is the speed limit which equals, as was indicated above, 4 km/sec

In order to apply these formulas for obtaining a theoretical distribution of the small craters by diameters, it is necessary to know the distribution of the meteorites either by their kinetic energies or by their mass and velocities.

5. Very little is known about both these distributions, and it is therefore necessary to introduce certain hypotheses. First of all, the observable material, as far as the meteorites in themselves are concerned, is negligible and there is no selection. For that reason, because of the continuous transition of the material into

a complex of small bodies, it is necessary to extrapolate these distributions which were obtained for meteors to heavy meteorites. Secondly, in the case of meteors it was also established that the indicated distributions were not sufficiently reliable. Distribution according to masses essentially depends on the exponent x in the equation

$$I^{*} = CM_0^x \nu_{\infty}^y \cos z \tag{2}$$

where

C is a certain constant

I^* is the force of light, which corresponds to the visual evaluation of the astral magnitude

M_0 is the mass of the meteor;

ν_∞ is the velocity of the meteor;

$x = 0.7$, if the visual evaluation pertains to the average brightness of the meteor, and $x = 1.0$, if this is an evaluation of the maximum brightness of the meteor; $y = 3$.

On these two assumptions, B. U. Levin (Ref. 3) has calculated the density of the meteoric bodies with a mass which is larger than M in the vicinity of the Earth's orbit (in the cgs system):

$$D_1(M) = \frac{9 \times 10^{-25}}{M^{0.84}} \text{ when } x = 0.7; \; D_2(M) = \frac{3 \times 10^{-25}}{M^{1.2}} \text{ when } x = 1.0 \tag{3}$$

In the calculations which follow, we will examine both variations.

In order to determine the distributions by velocities, the distribution of true radiants along elongations from the apex, extracted by B. U. Levin from the catalogues of Porter and the British Astronomical Association, was utilized. It was thereby assumed that all sporadic meteors travel over short periodic orbits with small heliocentric velocities. The validity of this assumption (which of course yields only a certain approximation to actuality) is confirmed by processing data of visual observations by Epic and radio location data from English observations. As an average, ν_h was accepted as $\nu_h = \nu_0(1.5)^{1/2} = 36.4$ km/sec, which corresponds to the semi-major axis a = 2a.e.

From the above-mentioned distributions of true radiants along elongations from the apex, it follows that 85% of the meteoric bodies are overtaking bodies. However, as was indicated by B. U. Levin, the density of the radiants in the vicinity of the antapex is lower and actually the fraction of overtaking bodies should be even larger. Calculations were conducted by two extreme hypotheses: first: the distribution of radiants along elongations is such that it follows from the calculation of B. U. Levin; second: all radiants of all meteors are distributed accurately in an antapex. The actual distribution obviously is located somewhere between those extremes.

With the above-adapted mean heliocentric velocity, the distribution of true radiants along elongations was converted into a distribution of meteoric bodies by selenocentric velocities. Knowing the distribution by masses and velocities, it is possible to calculate (taking into account the gravitational pull of the Moon) the number of meteoric bodies which fall with kinetic energies, with large somewhat fixed magnitudes in a unit of time (1 year) per unit of lunar surface (1 sq km), and consequently, also the number of small craters with diameters which are larger than some of the fixed diameters. For each of the variations of distribution by masses, calculations were made at two extreme assumptions on the distribution of velocity.

Here is a definition of the following hypotheses:

Ia. $D(M) = D_1(M)$; distribution by velocities obtained in accordance with the distribution of radiants along elongations (by B. U. Levin):

Ib. $D(M) = D_1(M)$; all meteors travel from an apex;

IIa. $D(M) = D_2(M)$; distribution by velocities as in Ia;

IIb. $D(M) = D_2(M)$; all meteors travel from an apex.

Table 1 gives the number of small craters which were formed in an area of 1 sq km of the lunar surface during the period of 1 year.

6. The observed distribution is obtained by a simple calculation on sufficiently detailed large-scale lunar charts. Such detailed large-scale charts are contained for example in the Atlas by Loewy and Puiseux (Ref. 4). It is necessary to select sectors, the simultaneousness of formation of which does not leave any doubt; the sectors should be sufficiently broad in order to obtain statistical accuracy, and it is desirable that a sector should be morphologically simple and homogeneous. All these conditions are well satisfied by, for instance, the lunar seas. The Sea of Moisture and the Sea of Tranquility were investigated. A number of small craters with various diameters are given in Table 2.

Table 1

Hypothesis	Diameter, km					
	>1	>2	>3	>4	>5	>6
Ia	1011.7×10^{-12}	197.4×10^{-12}	77.1×10^{-12}	31.0×10^{-12}	17.9×10^{-12}	11.0×10^{-12}
Ib	446.0×10^{-13}	77.6×10^{-13}	27.8×10^{-13}	13.5×10^{-13}	7.7×10^{-13}	4.9×10^{-13}
IIa	2207.4×10^{-16}	182.7×10^{-16}	41.8×10^{-16}	15.6×10^{-16}	6.8×10^{-16}	3.3×10^{-16}
IIb	385.0×10^{-17}	31.6×10^{-17}	7.3×10^{-17}	2.6×10^{-17}	1.2×10^{-17}	0.6×10^{-17}

Obviously, the course of numbers is of such a form and coincides with the theoretical numbers; as was mentioned above, this confirms once again the meteoric nature of these small craters.

The area of the Sea of Moisture is 4.90×10^4 km^2

The area of the Sea of Tranquility is 2.04×10^5 km^2

Table 2

	Diameter, km					
	>1	>2	>3	>4	>5	>6
Sea of Moistures	57	26	15	10	5	2
Sea of Tranquility	82	50	30	17	9	3

The observed condensations of the small craters (per 1 km^2) are given in Table 3.

7. In this manner, the ages (in years) of the indicated seas were obtained, as given for different variations of distributions by masses and velocities in Table 4.

As can be seen, the age which was obtained in the variation II, where $D(M) = D_2(M)$, is entirely improbable. However, for the purpose of selection there exists a criterion between the variations I and II which is based on the method itself. Actually various hypothesis which were used as a basis for calculation not only raise or lower the curve n(D) but also change its shape. The closest to reality will obviously be the case where there is the best coincidence of shape in curves n(D) and N(D). The value $|\Delta T|_{av}/T$, where T is the average age, obtained by small craters of

Table 3

	Diameter, km					
	>1	>2	>3	>4	>5	>6
Sea of Moistures	11.6×10^{-4}	5.3×10^{-4}	3.1×10^{-4}	2.0×10^{-4}	1.0×10^{-4}	0.4×10^{-4}
Sea of Tranquility	40.2×10^{-5}	24.5×10^{-5}	14.7×10^{-5}	8.3×10^{-5}	4.4×10^{-5}	1.5×10^{-5}

Table 4

Hypothesis	Sea of Moistures, Diameter, km						
	>1	>2	>3	>4	>5	>6	Average
Ia	1.15×10^{6}	2.68×10^{6}	4.02×10^{6}	6.45×10^{6}	5.58×10^{6}	3.63×10^{6}	3.92×10^{6}
Ib	2.60×10^{7}	6.82×10^{7}	11.1×10^{7}	14.8×10^{7}	13.0×10^{7}	8.15×10^{7}	9.41×10^{7}
IIa	0.525×10^{10}	2.90×10^{10}	7.40×10^{10}	12.8×10^{10}	14.7×10^{10}	12.1×10^{10}	8.40×10^{10}
IIb	3.01×10^{11}	16.8×10^{11}	42.4×10^{11}	76.8×10^{11}	83.3×10^{11}	66.5×10^{11}	48.1×10^{11}

Hypothesis	Sea of Tranquility, Diameter, km						
	>1	>2	>3	>4	>5	>6	Average
Ia	4.0×10^{5}	12.4×10^{5}	19.0×10^{5}	25.8×10^{5}	40.0×10^{5}	13.6×10^{5}	19.1×10^{5}
Ib	9.0×10^{6}	31.5×10^{6}	52.8×10^{6}	61.4×10^{6}	89.8×10^{6}	30.6×10^{6}	45.8×10^{6}
IIa	1.85×10^{9}	13.4×10^{9}	35.2×10^{9}	53.1×10^{9}	133.2×10^{9}	45.4×10^{9}	47.0×10^{9}
IIb	1.04×10^{11}	7.8×10^{11}	20.1×10^{11}	31.9×10^{11}	73.2×10^{11}	25.0×10^{11}	26.5×10^{11}

various diameters, and $|\Delta T|_{av}$ is the average value of the modulus of inclination of separate age values from the average, might serve as an obvious criterion of this.

The magnitude $|\Delta T|_{av}/T$ is given in Table 5.

Table 5

	Hypothesis			
	Ia	Ib	IIa	IIb
Sea of Moistures	0.37	0.38	0.57	0.57
Sea of Tranquility	0.48	0.48	0.66	0.65

As can be seen, variation I actually better reflects the real picture. Thus we conclude that the age of the Sea of Moisture is within the limits of 4 to 94 million years, and the Sea of Tranquility between the limits of 2 and 46 million years, depending upon which concentration of true radiants near the antapex was adapted. It might be said with sufficient conviction that the age of these seas is several tens of millions years. During the duration of this period of time, the implicit function on the constancy of meteoric activities is of course justified.

Obviously the ages are on one and the same order and both seas were created almost simultaneously.

8. What is the physical sense of the obtained age? Obviously (if we consider that the seas are former lava beds), this is the time which passed since the moment of complete hardening of the surface so that meteoric craters could be formed on it.

This age corresponds with the beginning of the Alpine mountain range formation on the Earth (Pacific Ocean period, the upper crust and the beginning of the Tertiary period). The obtained values of age should, of course, not be considered as final. It is desirable that works be repeated with better original data. It is, however, difficult to anticipate that this will essentially change the order of the obtained values. In any case, the insufficiency of the obtained data on the functions of distributions of mass and velocities of meteorites, do not give a possibility for a correction of the results.

Ashkhabad, November 1956.

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